Finite-Element Modeling of Acoustic Scattering from Objects in Shallow Water

David S. Burnett
Code HS11
Naval Surface Warfare Center
110 Vernon Ave. Panama City, FL 32407-7001
phone: (850) 235-5332 fax: (850) 234-4888 email: david.s.burnett@navy.mil

Kwang H. Lee
Code HS11
Naval Surface Warfare Center
110 Vernon Ave. Panama City, FL 32407-7001
phone: (850) 235-5981 fax: (850) 234-4888 email: kwang.lee@navy.mil

Gary S. Sammelmann
Code HS11
Naval Surface Warfare Center
110 Vernon Ave. Panama City, FL 32407-7001
phone: (850) 234-4618 fax: (850) 234-4888 email: gary.sammelmann@navy.mil

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LONG-TERM GOALS

The goal is to develop a state-of-the-art, high-fidelity, 3-D, finite-element (FE), broadband computer simulation capability for modeling the scattering of sonar signals by undersea objects located in or near the seabed in littoral environments with smooth or rippled water/sediment interfaces (Fig. 1). It is expected that most of the general computational techniques being developed in this effort will be able to be used in future ONR programs involving different applications.

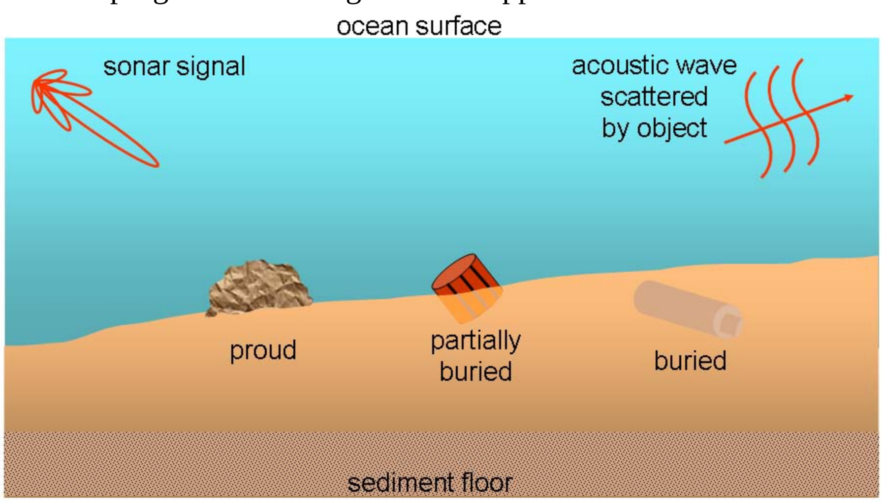

Figure 1. A representative shallow-water acoustic scattering scenario.

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14. ABSTRACT
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OBJECTIVES

The primary objective is to provide the U.S. Navy with a state-of-the-art computer simulation tool for modeling 3-D acoustic scattering from objects in littoral environments. A secondary objective is to maintain a continuing R&D effort in order to significantly increase the computational efficiency of the software, thereby expanding the ability to model more complex objects and at higher frequencies.

APPROACH

- **High fidelity**

To achieve high-fidelity models of elastic-wave propagation in man-made objects, the models employ 3-D continuum mechanics for every part of the object. Thin structural components, such as plates and shells, are modeled with 3-D elasticity theory, rather than plate or shell theories, because the latter employ 2-D physics inside 3-D geometry. However, the real-world physics is strongly 3-D near all structural discontinuities, e.g., corners and intersections of shells, as illustrated and explained in Fig. 2.

Part (a) of Fig. 2 shows a cross-sectional view of the ONR-labelled “Burnett T2” target, which was designed at NSWC-PC and built in FY06. It is a cylindrical shell with hemispherical endcaps and fill-ports on the endcaps. A circular partition at the mid-point of the length separates the interior into two compartments that can be filled with different fluids. The view shows the target slightly buried in sediment. Part (b) enlarges the region around the intersection of the partition and shell and identifies the common types of elastic and fluid waves in the vicinity of the intersection.

The essential concept here is that local 3-D evanescent elastic waves are usually generated at every structural discontinuity, e.g., intersections of structural components. The phases and amplitudes of the local evanescent elastic waves determine the phases and amplitudes of propagating elastic waves in the outer shell. These, in turn, determine the phases and amplitudes of the propagating acoustic waves in the water. The superposition of all such propagating waves coming from various parts of the object determine the resulting scattered wave in the far field. In short, the phases and amplitudes of elastic waves near structural discontinuities can have a significant influence on the acoustic far field. This use of 3-D elasticity for thin structural components, rather than the traditionally and universally used plate and shell theories, is a special feature of this project.

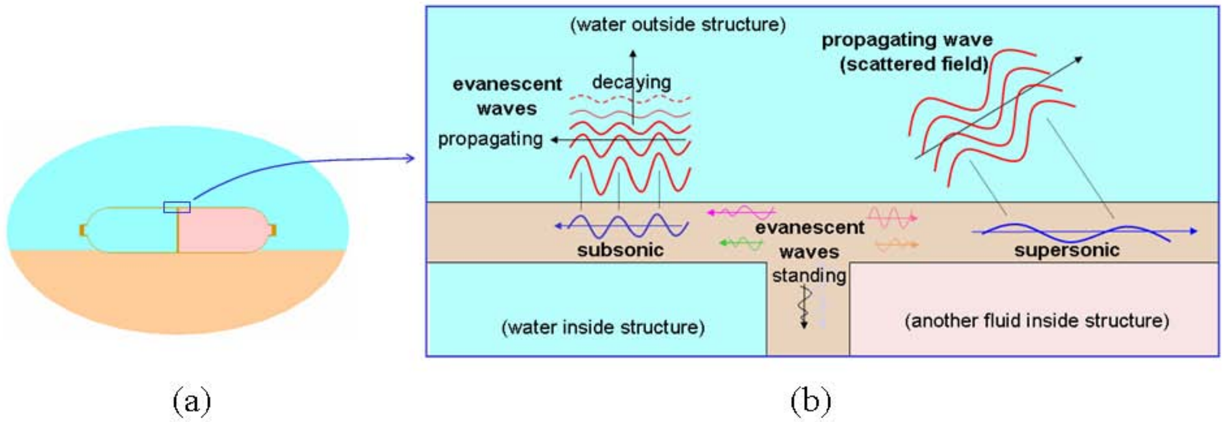


Figure 2. (a) Cross-section of a man-made object, showing intersection of structural components, (b) enlargement of intersection, showing types of elastic and fluid waves in the vicinity.

- **High speed**

All of the current projects, plus two new ones starting in FY08, involve 3-D FE modeling of acoustic scattering from undersea objects, requiring the computation of target strength (TS) as a function of both frequency and aspect. This involves a double sweep: (1) over a broad frequency band, typically about 200 frequencies, and (2), for each frequency, a sweep over a broad range of aspects, typically about 500 aspects. Therefore, about 100,000 3-D FE models will typically need to be run to produce a single frequency/aspect (F/A) data set. Such a data set is illustrated in Fig. 3, which is experimental data taken at NSWC-PC on the ONR-labelled “Burnett T1” target (same as the Burnett T2 target in Fig. 2(a) except that both compartments contain water.

Given the expected demands from several projects, a practical goal is to be able to compute a complete F/A data set, i.e., about 100,000 3-D FE models, in about one day. This goal is on its way to being accomplished, by a combination of software and hardware. The former has involved R&D to reduce the size of FE models and attain an *average* computational speed of several tens of seconds per model. The latter involves the design and construction of a distributed-processing rack-computer system. Progress on both fronts is described below.

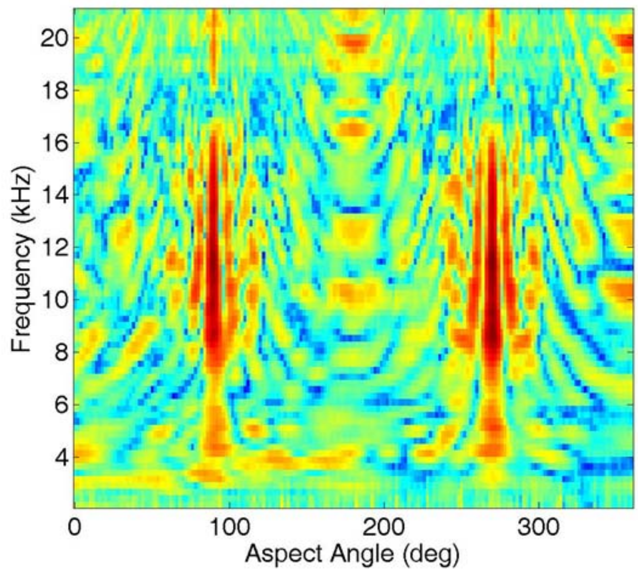


Figure 3. A typical F/A data set: experimental target strength of the Burnett T1 target.

- **High reliability**

The control of errors, via verification and validation ("V&V"), plays a key rôle in this project; it is essential to the goal of providing reliable simulations of the real world. Verification (Fig. 4) refers to the control of errors in the finite-element solution vis-à-vis the exact solution of the idealized mathematical model, i.e., computational/mathematical errors. Validation refers to the control of errors in the exact solution of the idealized mathematical model vis-à-vis the real world, i.e., errors in the physical assumptions and data in the idealized model. V&V is an ongoing, never-ending exercise as the simulation capabilities mature.

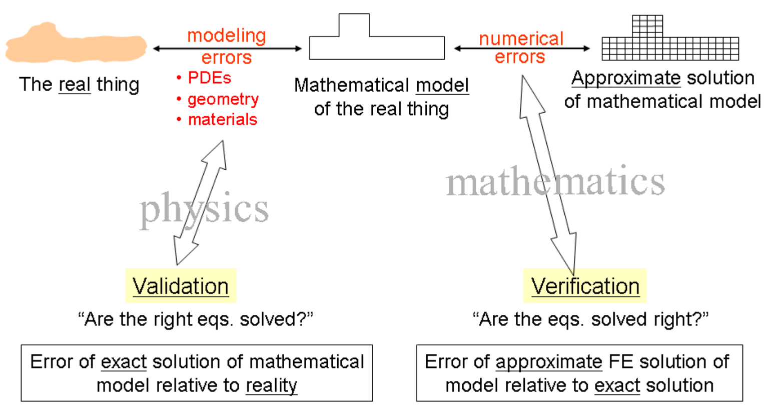


Figure 4. Pictorial explanation of verification and validation.

WORK COMPLETED

Several modeling techniques were developed in FY06 and described in the FY06 annual report. During FY07 those techniques were further enhanced, in terms of wider capability, robustness, computational speed, user interfaces and verification. The purpose of most of these techniques is to make the computational size of the FE model (number of degrees of freedom) as small as possible, in order to make it feasible to compute target response as a function of both frequency and aspect in a reasonable time, viz., to perform approximately 100,000 3-D analyses in about one day.

- **New radiation boundary conditions (RBCs), which reduce size of computational domain**

RBCs are boundary conditions prescribed on the outer surface of the finite volume of fluid surrounding the object; they approximate the exact Sommerfeld boundary conditions "at" infinity for an unbounded domain. The purpose of RBCs is to absorb the outgoing scattered wave when it strikes the finite fluid boundary of the computational domain. In FY06 NSWC-PC developed a new mathematical formulation for RBCs that can be applied to tri-axial ellipsoidal fluid boundaries, permitting the latter to more closely circumscribe high-aspect-ratio objects (Fig. 5). Tri-axial ellipsoidal geometries include prolate spheroidal, oblate spheroidal and spherical boundaries. In FY07 the formulation was extended to higher-order (for greater accuracy) and further enhanced by the addition of another technique. A manuscript for publication is in progress.

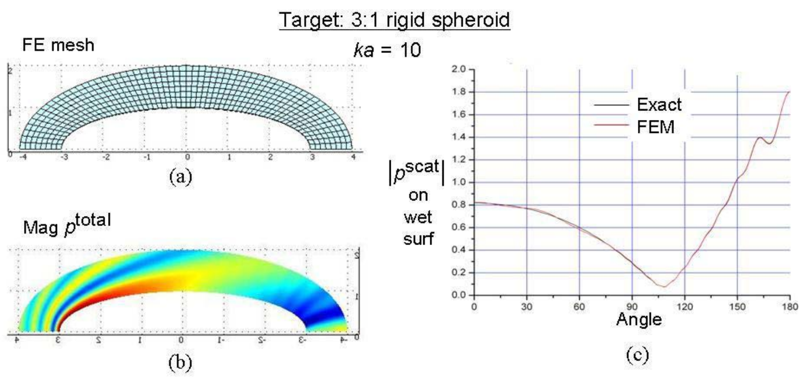
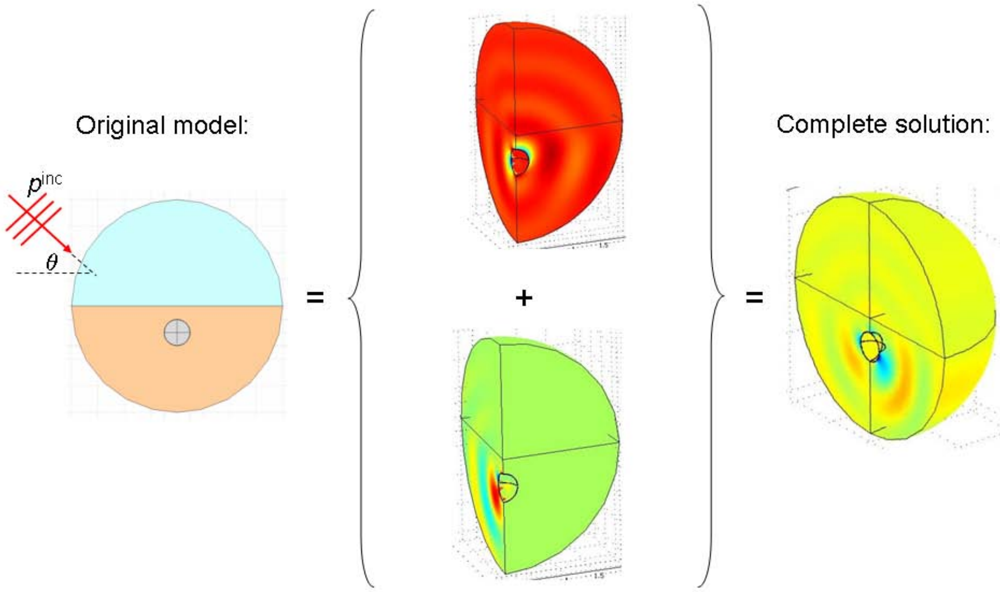


Figure 5. Verification of tri-axial ellipsoidal RBCs, for case of prolate spheroidal fluid boundary. (a) FE mesh for water surrounding a rigid prolate spheroidal object, (b) contours of magnitude of total pressure, (c) comparison of FE and exact solutions.

- **Group-theoretic decomposition of incident field, which reduces size of FE model**

When the object and the environment have certain types of common symmetries, *independent of the incident field*, the FE model can be reduced to a fraction of the full 3-D model by decomposing the problem into smaller parts, each of which runs exponentially faster than the original model. Figure 6 illustrates the technique for one plane of object/environment bi-lateral symmetry, although it is now operational for several planes of symmetry.



(a) (b) (c)

Figure 6. Reduction of problem. (a) the original problem, (b) decomposition into two related problems, (c) re-combination to form the complete solution.

This technique typically speeds up a 3-D analysis from one to two orders of magnitude. Most important, the speed-up is independent of the complexity of the incident field, i.e., it is independent of its smoothness or localization. For example, the computational cost is the same for a plane wave excitation as it is for a point force excitation. It is therefore very robust. [This is in marked contrast to the traditional axisymmetric Fourier decomposition, which is practical only for relatively smooth excitations.]

In FY06 a prototype modeling technique was developed and verified. In FY07 it was enhanced in several ways. A GUI was developed for a user-friendly interface, which automated all the symmetry operations. In addition, it was integrated with the Helmholtz far-field technique, described below.

- **Parametric sweeping: over frequency and aspect**

For F/A data sets it is essential that the FE software be able to sweep efficiently over frequency and/or aspect (ideally, both). A technique has been developed to enable Comsol to sweep very fast over aspect. This is illustrated in Fig. 7 for the so-called "Scenario 2" in the BMC project, in which the object is a slightly buried concrete conduit pipe. Without the sweeping technique, each 3-D analysis would take 280 seconds, so 200 aspects would take 200×280 = 56000 seconds, or 15.5 hours. With the technique, only the *first* aspect takes 280 seconds; each of the others takes only 4 seconds. Therefore all 200 models take only 1076 seconds, or an *average* of 5.4 seconds/model, which meets an important "high speed" goal described previously under Approach.

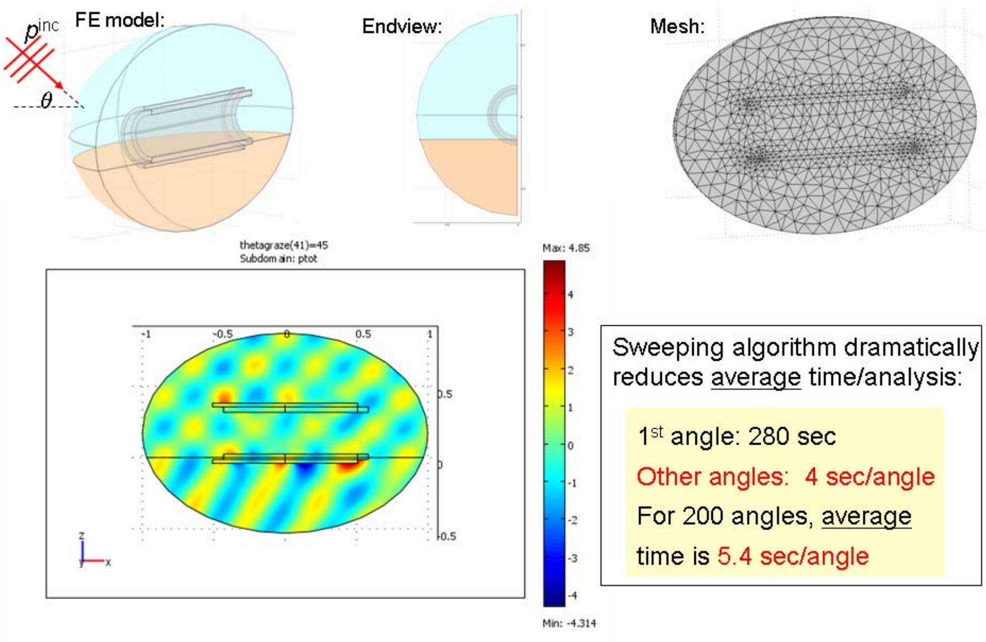


Figure 7. Sweeping algorithm dramatically reduces the average time/model. In example of a slightly buried concrete conduit pipe, average time/model reduced from 280 to 5.4 seconds.

- **Evaluation of scattered field exterior to the FE mesh, using Kirchhoff-Helmholtz integral**

For these ONR programs, the scattered field is usually wanted at the locations of receivers, i.e., at a few points or along a 1-D (curvilinear) track, which lie outside the FE mesh. This can be computed quickly using the classic Kirchhoff-Helmholtz integral, which uses the same 3-D physics as the Helmholtz PDE inside the mesh (Fig. 8).

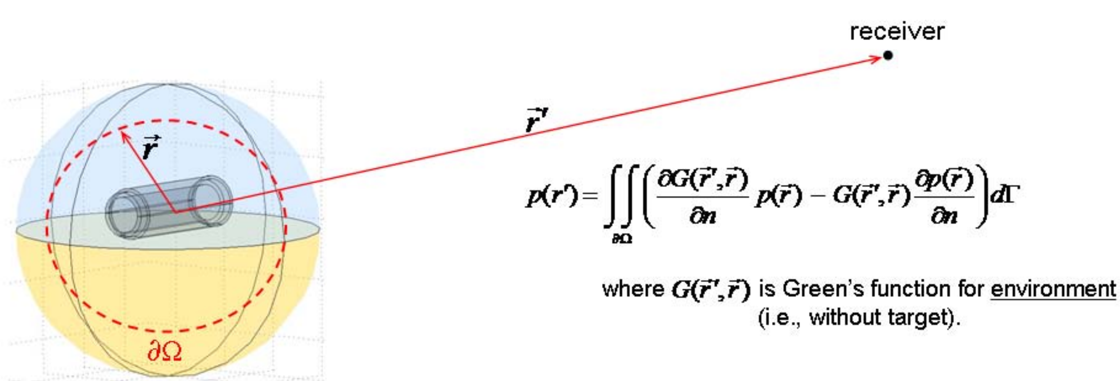


Figure 8. The Kirchhoff-Helmholtz integral and graphic depicting how it is used.

Dr. Gary Sammelmann implemented code for the Kirchhoff-Helmholtz integral. It imports the FE-computed scattered field and its normal derivative and computes the environmental Green's function, then evaluates the integral over a closed surface surrounding the object. This software was verified vis-à-vis a direct computation of the field inside the FE mesh, by using a larger-than-usual ball of water and sediment around a half-buried sphere so that the curved path along which the integral was evaluated lay inside the FE mesh (Fig. 9). Order 1% error was obtained, which could be lowered by a finer resolution.

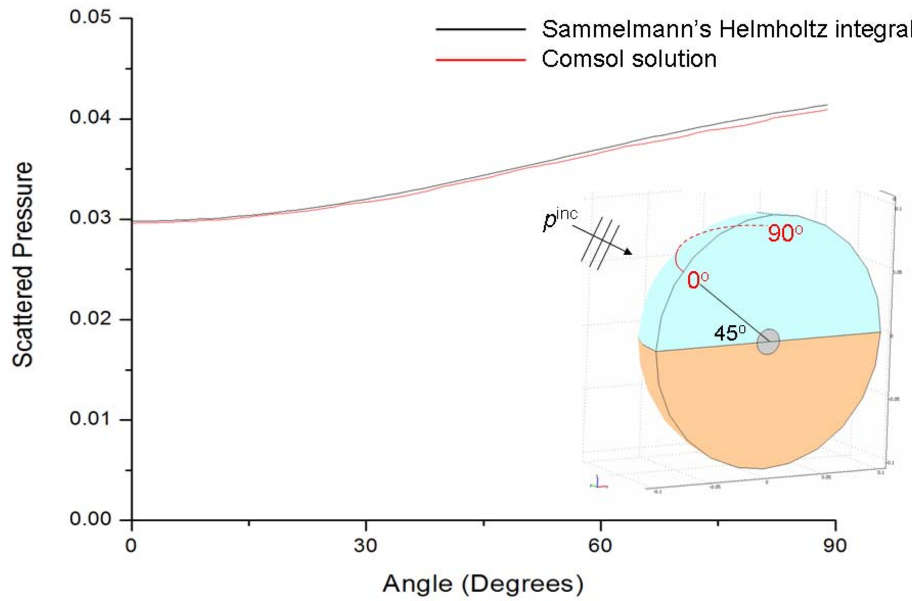


Figure 9. Verification of Sammelmann's Kirchhoff-Helmholtz integral algorithm vis-à-vis a Comsol Multiphysics FE solution.

- **Design and construction of a distributed-processing rack-computer system**

In 3Q06, NSWC-PC opened an account at the DoD High Performance Center (HPC) at Wright-Patterson Air Force Base (ASC/MSRC). At the time, this seemed to be the obvious way to go, i.e., leasing computer time on a very large distributed-processor system, rather than building our own.

However, it took ASC almost 8 months to test the Comsol Multiphysics FE software, after which a committee decided not to permit installation of Comsol Multiphysics, because of client/server security issues related to ASC's Kerberos software vis-à-vis Comsol's Chap software. The Comsol IT people were unsuccessful in trying to convince ASC that Chap was as effective as Kerberos. This concluded the HPC-approach, since it was deemed likely that the other HPC centers in the U.S. would likely come to the same conclusion.

Therefore, in April 2007, Dr. Burnett proposed to ONR that NSWC-PC build their own distributed-processing blade-architecture rack system. This was accepted by ONR. The specifications for the system have now been finalized, purchasing is underway and installation is planned for early FY08.

Concurrent with all the hardware efforts, software for managing a distributed-processing FE environment has also been under development. It will manage resources and apportion the load between processors, as well as automate the various techniques described above, in a manner transparent to the user. Substantial progress has been made on a user interface, including a GUI that will control the I/O for an entire F/A data set.

RESULTS

In FY05 Dr. Burnett decided to use the commercial FE code Comsol Multiphysics (then called Femlab) for modeling acoustic scattering from objects in shallow water. It appeared to have the essential physics capabilities and FE techniques for this kind of work, along with a powerful capability permitting users to incorporate their own mathematical expressions, of almost any complexity, in almost any part of the code. It is this latter feature that has made it possible to add the results of the above R&D to the Comsol software. Now, at the end of FY07, it is clear that the code has fulfilled its promise, performing well beyond initial expectations. It is an excellent platform for both R&D and production modeling, making possible all the research advances and modeling results described above. Looking ahead to FY08 and beyond, and considering R&D currently underway, it seems reasonable to expect that the code will be able to handle essentially all the modeling required on these ONR programs.

IMPACT/APPLICATIONS

This high-speed, high-fidelity 3-D target scattering simulation capability will be an important asset for SWAMSI, BMC, SAX04 and SERDP, since it will soon be possible to generate F/A data sets for many objects and environmental scenarios. The scientific impact will be all the new modeling techniques developed, which should be useful in other DoD programs as well as in the general structural acoustics community.

RELATED PROJECTS

- SERDP (Strategic Environmental Research and Development Program)

Assessing Sonar Performance Against Underwater UXO. Apply littoral target scattering modeling tools described herein to underwater UXO, focusing on characterization and remediation of UXO-contaminated environments.

- IAR (Independent Applied Research)

Detection and classification of MLO. Apply littoral target scattering modeling tools described herein to investigate D&C using cooperative, multi-vehicle UUV systems, with emphasis on impulse excitation at close range to excite LF resonances.

PUBLICATIONS

D. S. Burnett, "NSWC-PC Finite-Element Modeling Guide for 3-D Time-Harmonic Structural Acoustic Target Scattering", Dec. 2006 (technical report)